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CFD ANALYSIS OF CD NOZZLE AND EFFECT OF NOZZLE PRESSURE RATIO ON PRESSURE AND VELOCITY FOR SUDDENLY EXPANDED FLOWS

SHER AFGHAN KHAN[1], ABDUL AABID[2] AND MAUGHAL AHMED ALI BAIG[3]

[1,2]*Department of Mechanical Engineering, Faculty of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia*

[3]*Department of Mechanical Engineering, CMR Technical Campus, Hyderabad, Telangana, India*

ABSTRACT

A numerical work was carried out to study the effectiveness of micro-jets to control base pressure in suddenly expanded two-dimensional planar duct. Two micro-jets of 1 mm orifice diameter located at 90° intervals along a pitch circle distance of 1.5 times the nozzle exit diameter in the base region were employed as active controls. The calibrated Mach numbers at the entry to suddenly expanded duct was 1.87. The length-to-diameter ratio (L/D) of suddenly expanded duct was 10. Nozzles generating the calibrated Mach numbers were operated with nozzle pressure ratio (NPR) 3, 5, 7, 9 and 11. From the present investigation it is evident that for a given Mach number and effect of NPR will result in maximum increase/decrease of pressure and velocity. The convergent-divergent nozzle geometry has been modelled and simulated employing turbulence models: K-ε standard wall function turbulence model from the code was independently checked with the commercial computational fluid dynamics.

KEYWORDS: CFD, C-D Nozzle, ANSYS, Pressure & Mach Number

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Original Article

INTRODUCTION

An unexpected expansion of flow in subsonic and supersonic regimes is a major problem in many applications. In sudden expansion the effectiveness of jet plays a vital role in various application. In jet and rocket engine test cells it has been noticed that systems were used to simulate high altitude conditions; a jet discharging produces an effective discharge pressure which is sub atmospheric. Due to its wide application many scholars are studying the behaviour of fluid in sudden expanded duct. Khan et al attempted to control the base pressure with active control and some of the works relevant to the present study are reviewed in the next section to follow. However, to the best of the authors knowledge there is no work reported with active control of base pressure in simulation. Therefore, in the present study an attempt is made to investigate the base pressure control with active control in the form of micro-jets using Computational fluid dynamics (CFD) method by ANSYS FLUENT.

Computational fluid dynamics (CFD) is a versatile technique of modelling and simulation of flow fields which provides accurate results regarding the flow characteristics of an object. The solution of Reynolds averaged Navier-Stokes (RANS) equations being transient in nature imposes the complexity in the computational studies of

the flow field through suddenly expanded convergent-divergent (CD) nozzles and the implementation of an appropriate turbulence model for closure of the RANS equations. The compressible flow regions in nozzles being dominated by intense pressure gradients and complex secondary flows induce discrepancies between the numerical simulations and the experimental measurements.

The work outlined in this paper is to design a supersonic convergent-divergent (CD) Nozzle. The CD nozzles are designed on assumption of the compressible flow of the perfect gas. The effect of nozzle pressure ration is considered for Mach number 1.87. However, pressure and velocity flow in suddenly expanded duct has been observed by evaluating counters figures and plots. Moreover, A design procedure which can determine the configuration of suddenly expanded results (Sher Afghan Khan & Radhakrishnan, 2003) using CFD (ANSYS FLUENT) software.

LITERATURE REVIEW

Durst et al., (1974) demonstrated that in two-dimensional plane, symmetric flows can exist in sudden-expansion ducts for only a limited range of Reynolds numbers. At higher Reynolds number, at the tip of the sudden expansion small disturbance was generated and amplified in the shear layers which are formed between the main flow and the recirculation flow in the corners. Rathakrishnan & Sreekanth, (1984) studied flows in pipes with abrupt enlargement. They concluded that the non-dimensional base pressure depends and varies by parameters like expansion area ratios, the overall pressure ratios and the duct length-to-diameter ratios. They found that at a given overall pressure ratio and a given area ratio, we can find length-to-diameter ratio of the enlargement which shows minimum pressure loss in the nozzle at the nozzle exit on the symmetry axis. For minimum base pressure at given nozzle and enlargement area ratio, the duct length should exceed a fixed minimum value. In flow through pipes with sudden enlargement if the base pressure minimization is not adequate, hence the total pressure loss must also be considered to achieve most favourable performance. Khan et al., (2002-2012) Experimentally explained the usefulness of micro-jets to control base pressure in a suddenly expanded axisymmetric duct by considering parameters like different Mach number, area ratio, NPR, and length-to-diameter (L/D) ratio in expansion of a CD nozzle with and without control of fluid flows. However, it was found that no numerical and analytical study was explained to control the base pressure at CD nozzle from micro-jets.

The numerical and experimental studies carried out by various scholars have evaluated the accuracy of the turbulence model for expecting the flow field and the nozzle performance precisely. Two-dimensional axisymmetric compressible flow analysis through a CD nozzle has been studied with the help of ANSYS FLUENT by using K-ε turbulence model and Spalart-Allmaras turbulence model, a comparative investigation between the models on the basis pressure, velocity, temperature contours and vectors to ascertain the efficient design conditions for CD nozzles also been done by Najar et al., (2013).

The variation of flow parameters like Pressure, Temperature, Velocity and Density is visualized using CFD and also determined the simulation of shockwave (Patel et al., 2016). Zhang & Kim, (2017) theoretically and numerically studied the particle–gas flows through a CD nozzle. Homogeneous and equilibrium model for no slip condition in velocity and temperature occurs between particle and gas phase considered to derive mass flow rate and speed of sound for multiphase flows. Particle mass loading to investigate its effect on choking phenomena for particle–gas flows at different nozzle pressure ratios has been carried. CFD simulation code and Solid works CAD tool for modelling used and analysed the results. In this performance observed that the fluid leaves the throat and proceeds to the divergent region of the CD nozzle. This proves distribution of pressure in the nozzle as flow accelerates sub-sonically or super-sonically with

reduction in pressure drop (Ajoko & Tuaweri, 2017).

PROBLEM DEFINITION

Fluid flow systems are required for high altitude motor test facilities. The geometry of the CD nozzle based on the designed Mach number is shown in figure 1. Micro-jets are designed 1mm of diameter and located at the pitch distance of 1.5 mm from the divergent diameter. The purpose of the research is to analyses the flows through the CD nozzle and prediction of theoretical flow parameters such as pressure and velocity with the effect of different parameters proving by CFD simulation in 2D modelling with and without micro-jets.

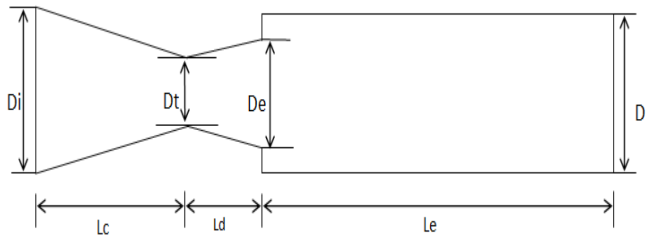


Figure 1: Geometry of CD Nozzle with Enlarged Duct

The dimensions of CD nozzle with suddenly expanded duct are mentioned in table 1.

Table 1: Dimension of CD nozzle for Mach number 1.87

Mach Number	1.87
Inlet diameter (Di)	28.72 mm
Throat diameter (Dt)	8.648 mm
Exit diameter (De)	10 mm
Extended diameter (D)	25 mm
Convergent length (Lc)	35 mm
Divergent length (Ld)	12.926 mm
Extended length (Le)	250 mm
Micro-jets diameter (Dm)	1 mm

FINITE ELEMENT MODELLING

In finite element modelling, the fluid flow variation on CD nozzle can be observed by using ANSYS FLUENT 18.0 software.

Two-Dimensional CD Nozzle

For two-dimensional model ANSYS workbench was used to model the geometry of CD nozzle and considered 2D planar body in this case. Boundary conditions are defined by considering edges of the plane to initiate the solution with perfect ideal flow. The 2D planar finite element model is shown in figure 2. For meshing, ANSYS workbench were used and created structural mesh to enhance fine mesh. Total, 21,368 binary nodes, were generated for 2D planar model.

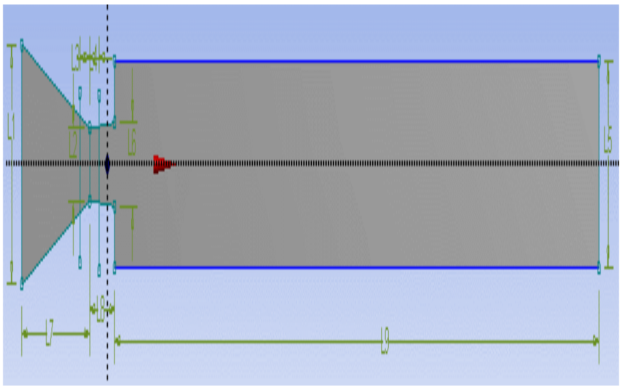


Figure 2: 2D Planar Fluid Body

Calculation Procedure

Calculation of flow characteristics inside the adopted control volume were performed using RANS (Reynolds-Averaged Navier-Stokes) equations with k-ε standard turbulent model (ANSYS Inc, 2017). The most important settings that have been applied are;

- Solver: steady, absolute, 2D planar pressure-based
- Model: viscous, k-ε standard wall function, Energy equation
- Fluid: air, ideal gas, viscosity by Sutherland law, three coefficient methods
- Boundary conditions: inlet, pressure inlet (pa); outlet, pressure outlet; wall, wall
- Solution method: Pressure (standard); density, momentum, turbulence kinetic energy, turbulence dissipation rate, energy (second order upwind)
- Solution initialization: standard, from inlet
- Reference value: inlet (solid surface body)

Validation of Finite Element Results

In order to validate the finite element model, the CD nozzle with micro-jets control at the base and expanded duct placed on the divergent portion of the CD nozzle in figure 1 of (Khan et al., 2002) is considered. By comparing the results obtained by (Khan et al., 2003) and the present finite element results, there is a good agreement as shown in table 1.

Table 2: Verification of Present Finite Element Model

Pressure	Khan et al., 2002 (Experimental)	Present work (Simulation)
Without control at base (Pb) (NPR 3)	-18.79	-21.55
With control at base (Pb) (NPR 3)	-17.88	-18.87

RESULTS AND DISCUSSIONS

The aim of research to identify the fluid flow on CD nozzle with and without micro-jets control for a suddenly expanded duct by effect of nozzle pressure ratio on pressure and velocity plots for Mach number 1.87.

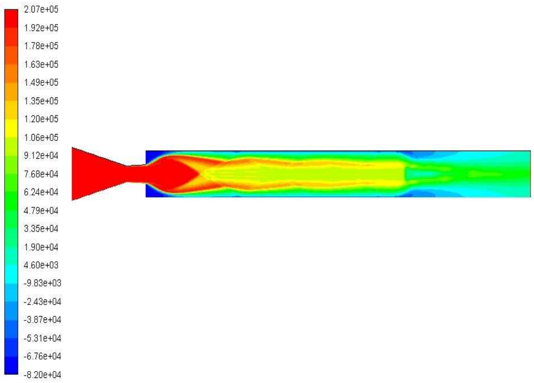
The problem definition as stated in the figure (1) is simplified by observing the fluid flows for each case and identified the effect nozzle pressure ratio (NPR). To obtained this, numerical study was performed and verified each. The advantage of this study is to investigate the perfect fluid flow and active control of pressure micro-jets at the base.

Effect of NPR on Pressure

The figure 3 shows the total pressure variation from the inlet to the outlet of the CD nozzle by considering contours without control of micro-jets. Similarly, the figure 4 shows the total pressure variation from the inlet to the outlet of the CD nozzle by considering contours with control of micro-jets. In figure 3 and 4 depicts blue colour at the expanded duct immediate after divergent portion which represents base pressure that suddenly decreases and emerging rotational flow. The value of base pressure is divided into atmospheric pressure (Pa) 98273 pascals and figure 5 (b) illustrated the base pressure versus wall position. Plotted the static, and base pressure (Pb) for each NPR shown in figure 5 and it shows the pressure losses when it varies through the wall of the nozzle in both cases, but variation is different for each. The table 2 illustrate the values of total pressure for an effect of nozzle pressure ration with and without micro-jets control. The value of base pressure is considered from the suddenly expanded duct diameter at the divergent of the nozzle. Finally, the figure 6 show that the loss of pressure is minimum when micro-jets installed at the base and flow of rotation also become control.

Table 2: Effect of NPR on total pressure for suddenly expanded flows

S. No.	NPR	Without Control Values			Micro-Jets Control Values		
		Inlet	Outlet	Net	Inlet	Outlet	Net
1	3	196546	25276.552	116841.31	196546	42033.086	127220.39
2	5	393092	135319.36	273130.79	393092	191070	302450.4
3	7	589638	265294.43	438696.28	589638	394868.16	502250.24
4	9	786186	410618.92	611406.09	786186	583288.93	695151.78
5	11	982730	597523.73	803464.24	982730	803358.1	902250.86



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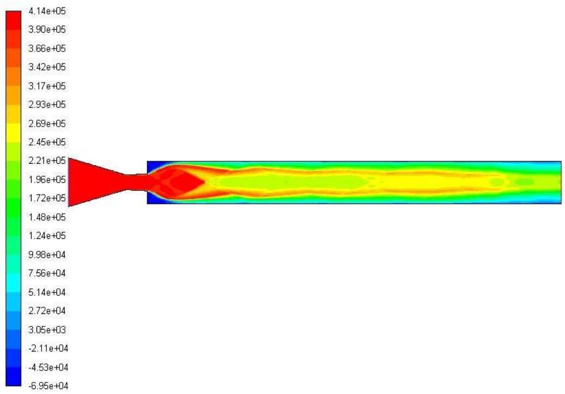

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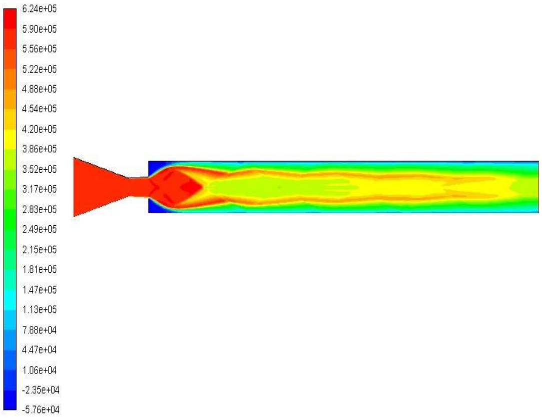

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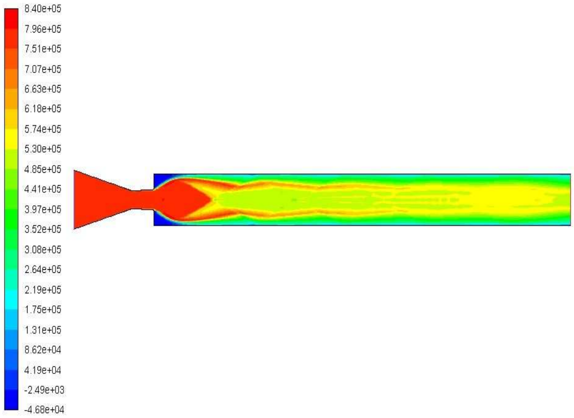

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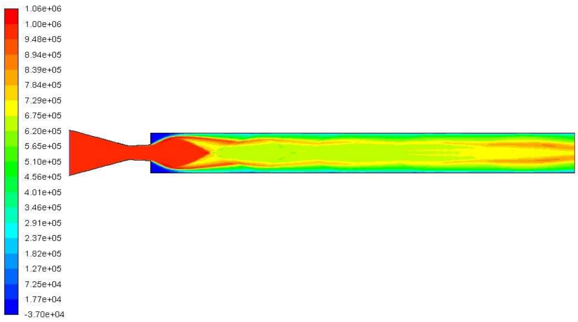
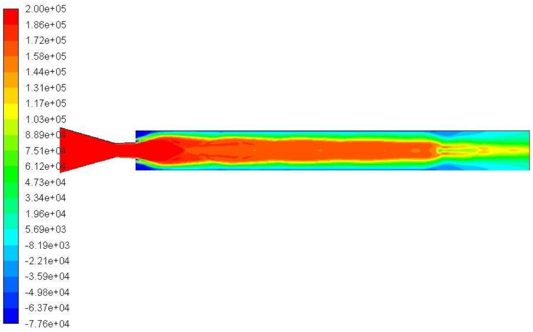


(e)

Figure 3: Total Pressure Contours

(a) NPR 3 (b) NPR 5 (c) NPR 7 (d) NPR 9 (d) NPR 11



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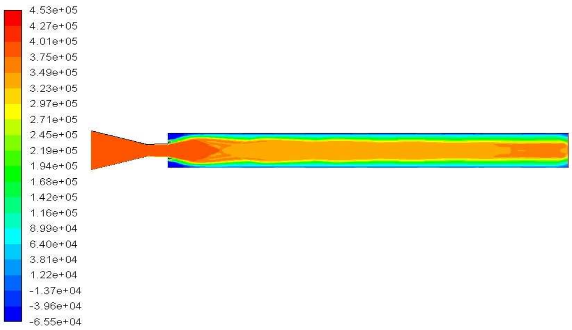

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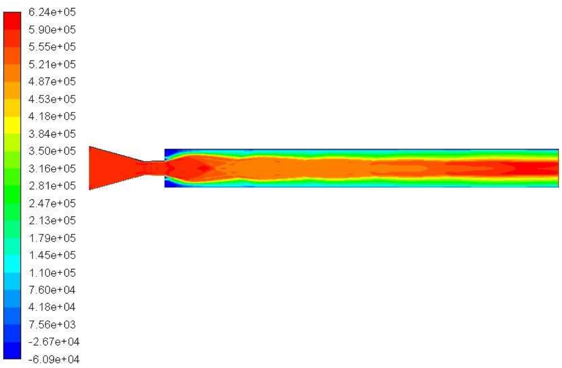

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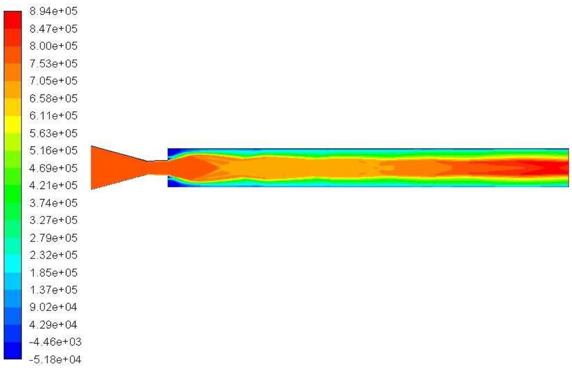

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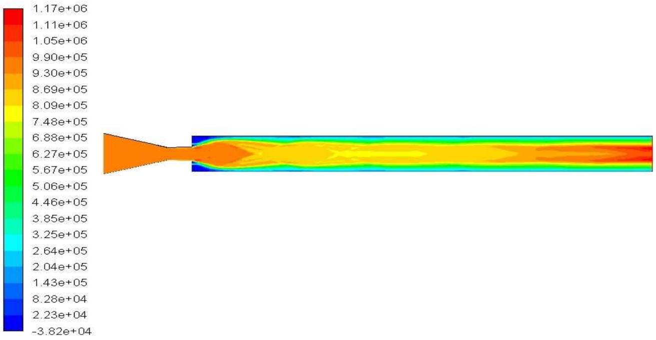
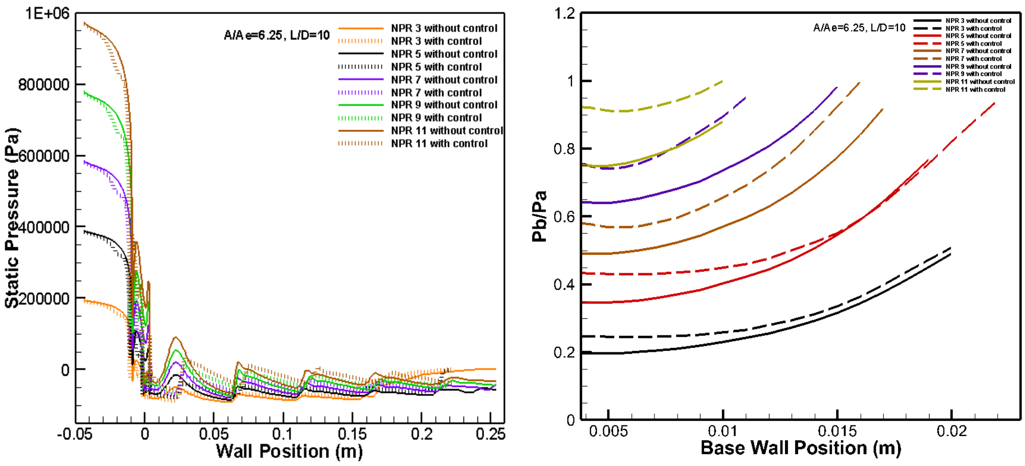


(e)

Figure 4: Total Pressure Contours with Micro-Jets Control for (a) NPR 3 (b) NPR 5 (c) NPR 7 (d) NPR 9 (d) NPR 11



(a) **(b)**

Figure 5: Effect of NPR for (a) Static Pressure (b) Base Pressure

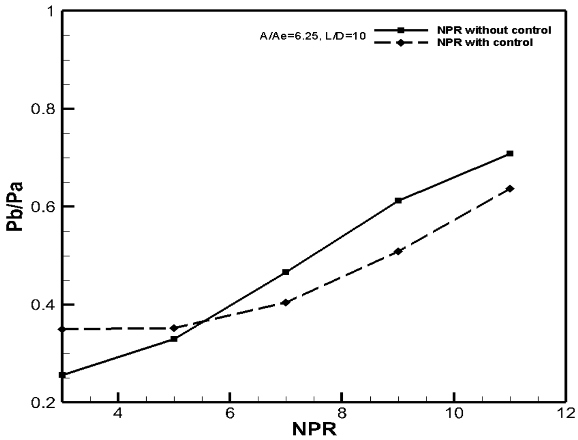


Figure 6: Effect of NPR Vs Base Pressure

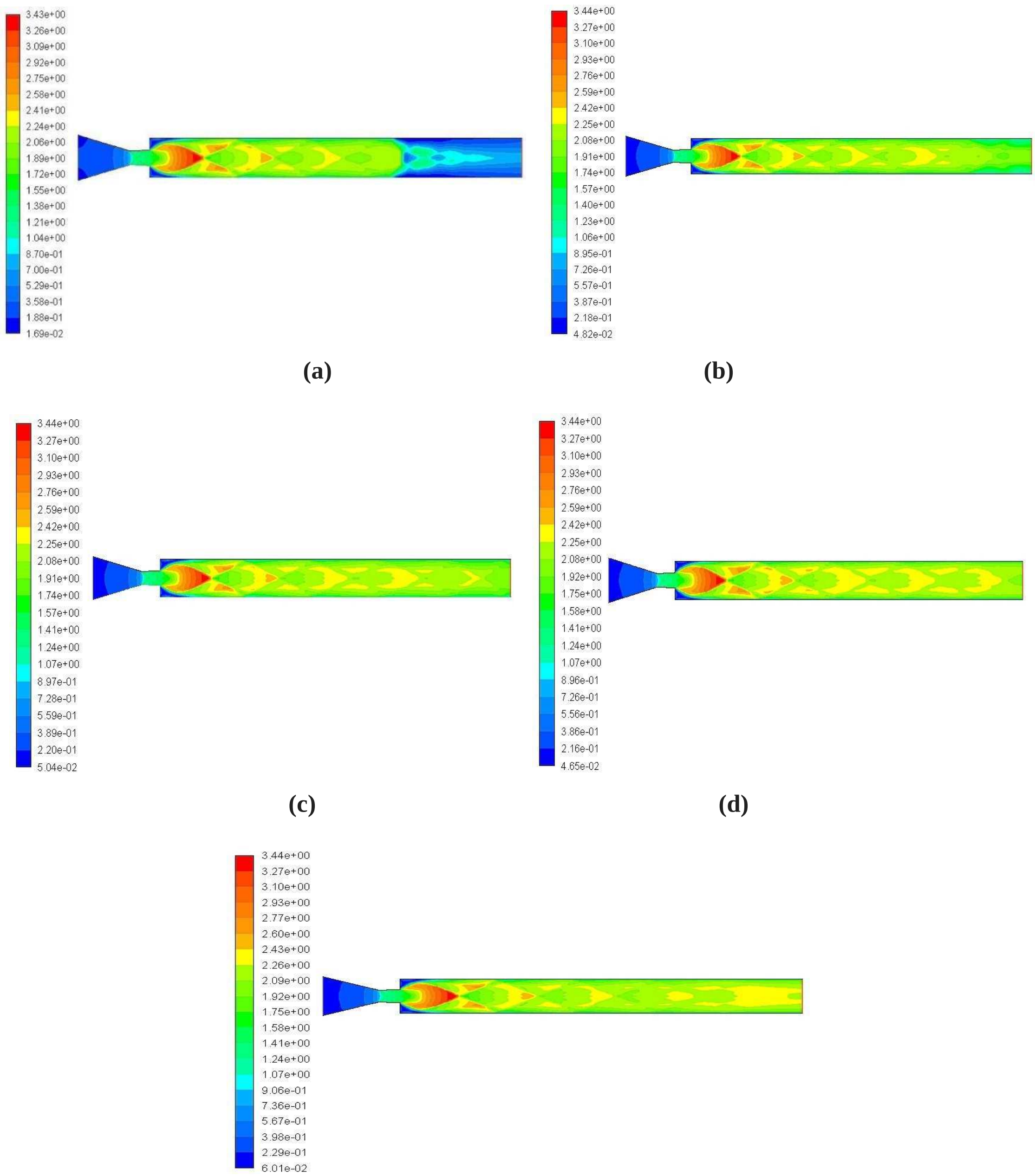
Effect of NPR on velocity (Mach Number)

The velocity considering Mach number in a fluid body is also important. The figure 7 & 8 shows the Mach number variation from the inlet to the outlet of the CD nozzle by considering contours and XY plot. Consequently, XY plot shown in figure 9 Mach number increases when it varies through the wall of the nozzle. The table 3 illustrate the values of

Mach number for an effect of nozzle pressure ration.

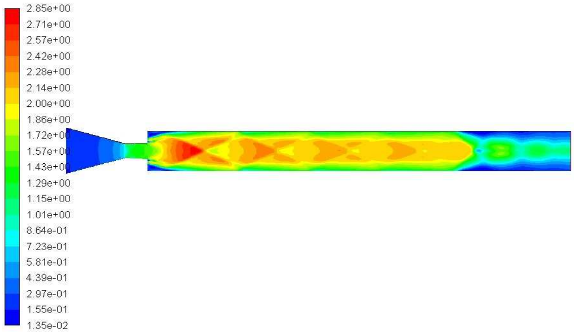
Table 3: Effect of NPR on Velocity (Mach number) for Suddenly Expanded Flows

S. No	NPR	Without Control Values			Micro-Jets Control Values		
		Inlet	Outlet	Net	Inlet	Outlet	Net
1	3	0.175187	0.539864	0.344899	0.257959	0.65911	0.437947
2	5	0.175193	1.69734	0.883566	0.279884	1.37002	0.768999
3	7	0.175199	1.85001	0.954618	0.285490	2.02438	1.06568
4	9	0.175186	2.01312	1.03051	0.291804	2.13846	1.12034
5	11	0.175205	2.10656	1.07402	0.308279	2.24143	2.24143



(a) (b) (c) (d) (e)

Figure 7: Mach Number Contours for (a) NPR 3 (b) NPR 5 (c) NPR 7 (d) NPR 7 (e) NPR 11



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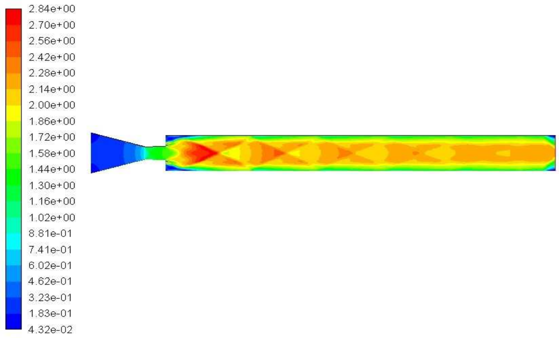

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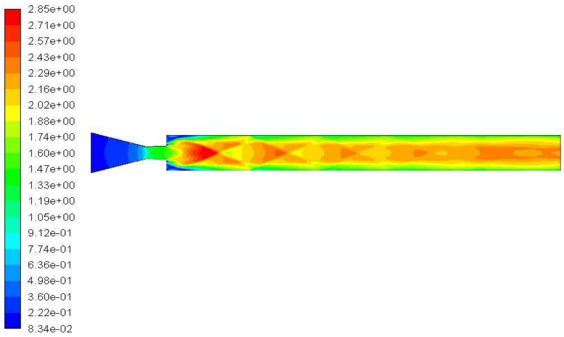

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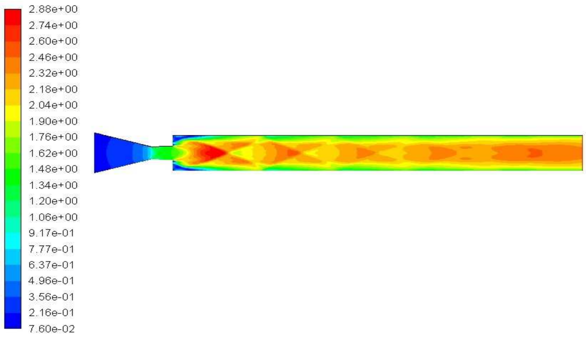

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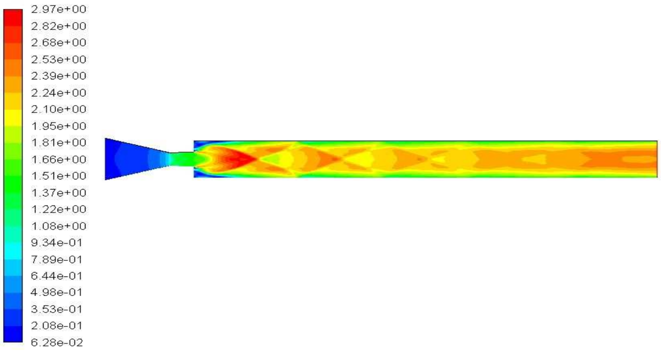


(e)

Figure 8: Mach number Contours with Micro-Jets Control for (a) NPR 3 (b) NPR 5 (c) NPR 7 (d) NPR 7 (e) NPR 11

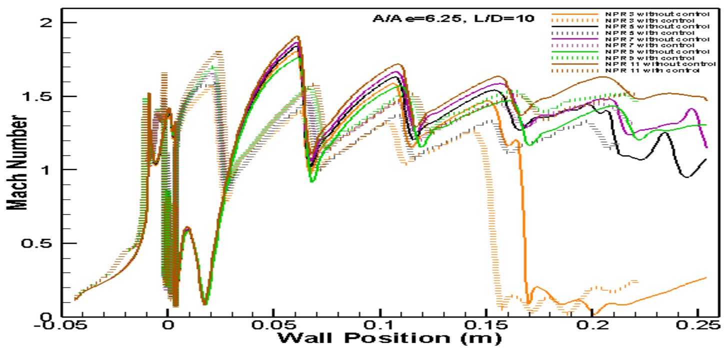
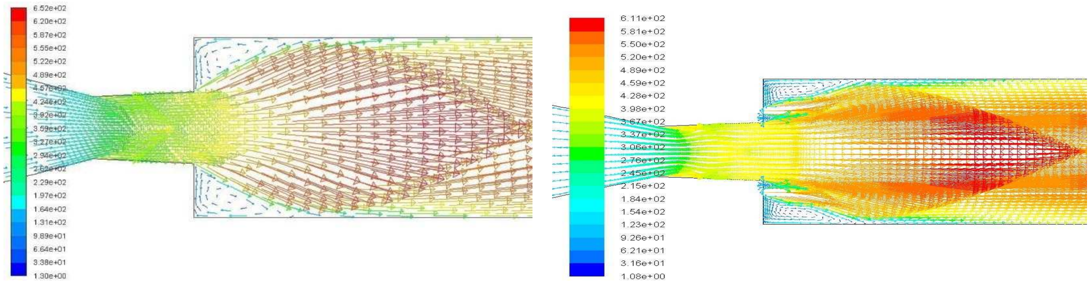


Figure 9: Effect of NPR for Mach Number with and without Control

In figure 10(a) there is no flow control due to this the pressure suddenly decreases and creating shocks at the exit of the divergent and at the base flow of pressure become high therefore the shocks may have chance to increase drag at the expanded duct. To control this small diameter of micro-jets are used shown in figure 10(b). The effect of micro-jets is proved at the base the rotation flow of air decreased.

Furthermore, to control the base pressure Khan et al., (2002-2012) experimentally investigated with and without control of fluid flows in a CD nozzle with effect of NPR, area ratio and L/D of expanded nozzle. Similarly, for NPR 5, 7, 9 and 11 the velocity vector results approximately same rotational flows at the base of expanded duct only it slightly differs in area as compared to NPR 3.



(a) (b)

Figure10: Velocity Vector for NPR 3 (a) without Micro-Jets Control (b) with Micro-Jets Control

CONCLUSIONS

The effect of the NPR on pressure and velocity for suddenly expanded convergent-divergent nozzle and active control in the form of micro-jets to control base pressure level has been demonstrated using ANSYS workbench 18.0. The base pressure assumes ratio area 6.25 and L/D = 10 at 1.87 Mach number. The micro-jets are found to be effective for a given Mach number and NPR. The enlarged duct wall pressure distribution is not adversely influenced by the active control. Based on the above results we conclude that, total pressure dramatically varying from inlet to the outlet and value of pressure is high for NPR 11 as shown in table 2. As pressure decreases velocity will increase and our results proved that the velocity is high at the exit and variation of pressure inlet to the outlet is observed by considering Mach number shown in table 3.

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